

HARD AND SOFT QCD IN CHARMONIUM PRODUCTION[†]C.B. MARIOTTO^{1,2}, M.B. GAY DUCATI¹, G. INGELMAN²¹ *Instituto de Física, Univ. Federal do Rio Grande do Sul,
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We show that both hard perturbative and soft non-perturbative QCD effects are important in hadroproduction of charmonium. Observed x_F and p_\perp distributions of J/ψ in fixed target experiments can be well described by our Monte Carlo model based on perturbative QCD and the Color Evaporation Model.

Aiming at an understanding of non-perturbative QCD (non-pQCD), we study effects of soft color interactions on charmonium production. This is a particularly interesting case, since the charm quark mass m_c is a large enough scale for perturbative QCD (pQCD) to be used as a basis, but small enough for non-perturbative effects to be of importance. This provides an interesting interplay between hard and soft QCD dynamics.

In the Color Singlet Model¹ (CSM) a colour singlet $c\bar{c}$ pair is produced in a conventional pQCD process. However, this model gives a cross section more than one order of magnitude lower than the observed one for high- p_\perp charmonium at the Tevatron². This surprisingly high rate can be reproduced well by the Color Evaporation Model (CEM)³ and the Soft Color Interaction⁴ model which not only include conventional pQCD but also aspects of non-pQCD dynamics. In essence, a perturbatively produced $c\bar{c}$ pair in a color octet state can be transformed into a color singlet state through soft gluon exchange.

In CEM a simple statistical color factor $1/9$ gives the probability that a $c\bar{c}$ pair is in a singlet state. For pairs with mass below the threshold for open charm production, $m_{c\bar{c}} < 2m_D$, the fraction giving a J/ψ is given by an additional non-perturbative parameter $\rho_{J/\psi} = 0.5$. We have earlier found⁵ that CEM can replace the Pomeron-based model⁶ to describe photoproduction of J/ψ and D . As a result of our further investigation of the CEM model, we here present preliminary results for the x_F and p_\perp distributions of J/ψ in hadroproduction.

The total cross section for J/ψ in hadroproduction was calculated analytically using leading order (LO) QCD, where the contributing processes are $gg \rightarrow c\bar{c}$ and $q\bar{q} \rightarrow c\bar{c}$. Our results in fig. 1 show an energy dependence in agreement with data. However, an overall normalisation factor $K = 3.3$ was

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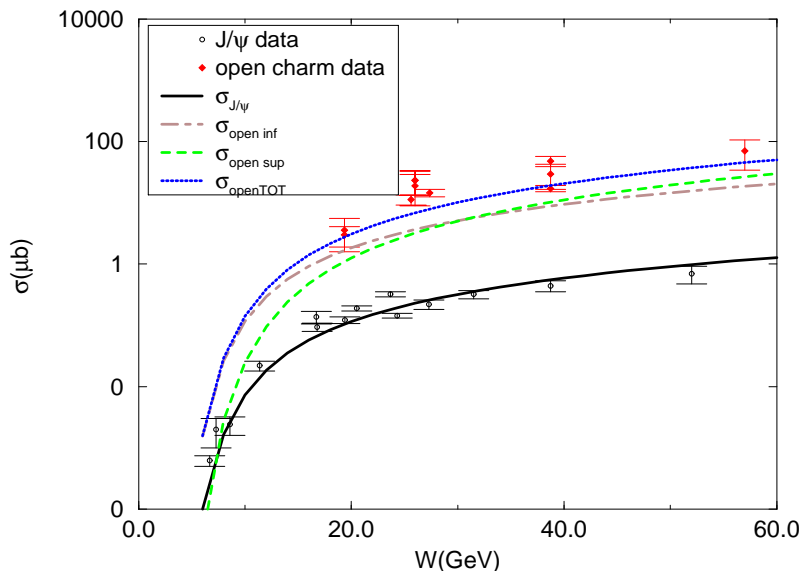


Figure 1: Total cross section of J/ψ and open charm (D) in hadroproduction as obtained with CEM based on the LO pQCD subprocesses and including a factor $K = 3.3$. The curves $\sigma_{open\ sup}$ and $\sigma_{open\ inf}$ are the contributions to open charm for $m_{c\bar{c}}$ above and below $2m_D$, the latter for $c\bar{c}$ in a color octet state.

needed in order to describe the data. This may be attributed to either higher order pQCD corrections that were not included in our calculation, or to some soft dynamics that could also play an important role.

In order to understand the origin of this K -factor, we studied also some important differential distributions, namely x_F (longitudinal momentum fraction) and p_\perp of J/ψ in fixed target experiments. For this purpose we have added the Color Evaporation Model to the PYTHIA⁷ Monte Carlo program so that complete events can be simulated. The LO pQCD processes are the same as described above with the charm mass included in the matrix element. The importance of higher order pQCD contributions was estimated by the initial and final state parton showers where a $c\bar{c}$ pair can be produced. In this case we include all $2 \rightarrow 2$ processes ($gg \rightarrow gg$, $qg \rightarrow qg$, $qq \rightarrow qq$ etc) as hard scattering basis, except those producing a $c\bar{c}$ to avoid double counting.

Our results are shown in fig. 2, where the x_F and p_\perp distributions of J/ψ are compared to fixed target data⁸. With a charm mass $m_c = 1.3\text{ GeV}$, there is no need for a K factor, provided the higher order pQCD contributions and the soft color effects are included. Thus, both higher order pQCD and soft effects are important.

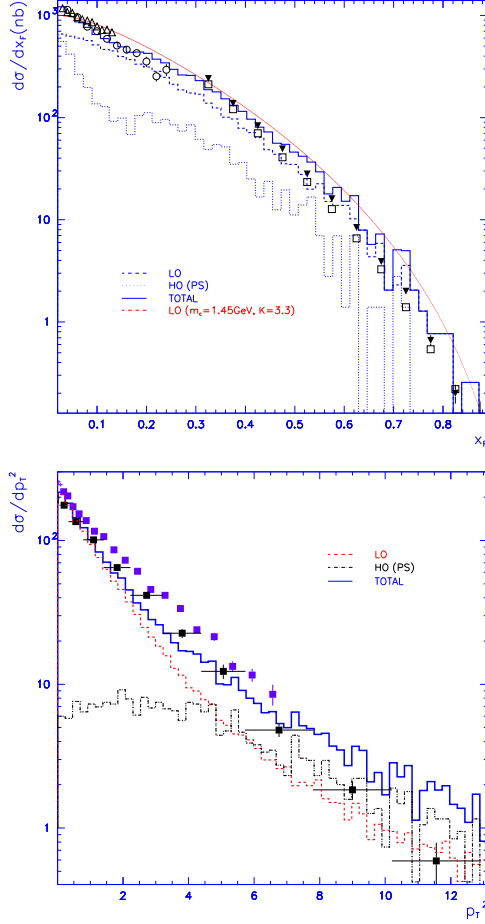


Figure 2: Distributions in x_F and p_{\perp}^2 of J/ψ in fixed target hadroproduction with $E_{beam} = 800 \text{ GeV}$. Data⁸ compared to CEM results based on leading order (LO) matrix elements and higher orders (HO) estimated by parton showers, and their sum (full histogram). Also shown for x_F (thin full curve) is the LO result with $m_c = 1.45 \text{ GeV}$ and $K = 3.3$.

The higher order pQCD gives important contributions at small x_F and large p_{\perp} . The distribution in p_{\perp} gives further insights on the interplay between hard and soft processes. The data can be reasonably well described by a gaussian of width 1 GeV , which suggests that both hard and soft contributions are present. The model has three basic sources giving transverse momentum to the J/ψ . The first is from the pQCD processes described by the $2 \rightarrow 2$ matrix elements and by the parton showers. The LO $c\bar{c}$ process dominates strongly the

J/ψ production at low p_\perp , but not at larger p_\perp because a larger momentum transfer in the $2 \rightarrow 2$ process leads to $M_{c\bar{c}} > 2m_D$ and open charm production. Instead, the higher order pQCD processes, where typically a gluon from the LO $2 \rightarrow 2$ process splits into a $c\bar{c}$ pair, is important for the J/ψ production at larger p_\perp as can be seen in fig. 2b.

The two other sources of transverse momentum are due to soft dynamics. One is the Fermi motion of partons inside the initial state hadrons, for which we use the conventional gaussian distribution with $\langle k_T^2 \rangle = (0.59 \text{ GeV}/c)^2$ used in PYTHIA. The other source is the soft momenta that may be associated with the soft gluon exchange that neutralize color. We model this source by giving the $c\bar{c}$ pair an additional p_\perp in random direction using the same gaussian distribution as for the soft Fermi motion. This results in a reasonable description of the data as shown in fig. 2b. Thus, both hard pQCD and soft non-pQCD effects should be considered in order to understand the observed p_\perp distribution.

In conclusion, we have found that both higher order pQCD and soft non-pQCD effects are important for the understanding of charmonium production. The soft interactions can be successfully modelled, e.g. by the Color Evaporation Model which we have made more dynamically explicit by implementing it in the PYTHIA Monte Carlo. Simulated events then give access to more detailed information on J/ψ production. Our results, which depend on a few parameters related to basic unknown features of non-pQCD, provide a reasonable description of the overall cross section of J/ψ in hadroproduction, without the use of an arbitrary K -factor. The differential distributions in x_F and p_\perp of the J/ψ are also well reproduced.

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References

1. M. Kr mer, *Nucl. Phys. B* **459**, 3 (1996).
2. F. Abe *et al*, *Phys. Rev. Lett.* **75**, 4358 (1995).
3. J.F. Amundson *et al*, *Phys. Lett. B* **390**, 323 (1997).
4. A. Edin, G. Ingelman, J. Rathsman, *Phys. Rev. D* **56**, 7317 (1997).
5. M.B. Gay Ducati, C.B. Mariotto, *Phys. Lett. B* **464**, 286 (1999).
6. M.G. Ryskin *et al*, *Z. Phys. C* **76**, 231 (1997).
7. T. S strand, *Computer Phys. Commun.* **82**, 74 (1994).
8. M.S. Kowitt *et al*, *Phys. Rev. Lett.* **72**, 1318 (1994).
M.H. Schub *et al*, *Phys. Rev. D* **52**, 1307 (1995).
T. Alexopoulos *et al*, *Phys. Rev. D* **55**, 3927 (1997).